**A Letter of Intent to Jefferson Lab PAC-27**

# Measurement of Meson Cloud in the Nucleon

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**Abstract:** We propose to measure DIS scattering off hydrogen and deuterium targets in coincidence with low momentum recoiling protons (or pairs of protons). The primary goal of this experiment is to measure the pion structure functions at the valence-quark region using the Sullivan process. The proposed measurements would also determine the magnitude of the pion-cloud component in the nucleon. A quantitative measurement of the pion-cloud component in the nucleon is important for extracting accurately the neutron structure function in the upcoming BONUS tagged-proton DIS experiment on deuterium target. The proposed experiment will use a 6 GeV unpolarized electron beam. Scattered electrons will be detected using the CLAS spectrometer. The recoiling low-momentum protons (or proton pairs in the case of deuterium target) will be measured using the BONUS detector currently under construction.

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## Contents

## 1 Physics Motivation

In early 1970s, Sullivan [1] pointed out that the electron Deep Inelastic Scattering (DIS) off a proton target includes a contribution originating from a scattering off the meson cloud of the nucleon (Fig. 1). This so-called Sullivan process was shown to persist even at large $Q^2$ scales. An immediate consequence of the Sullivan process is that the nucleon parton distributions contain a component which can be attributed to the meson cloud. This intriguing idea remained untested for many years.

In the early 1980s, Thomas [2] predicted several implications of the Sullivan process for nucleon parton distributions using a cloudy-bag model for describing the meson cloud. In particular, it was predicted that the nucleon sea should have an up/down sea-quark flavor asymmetry, as well as an $s/\bar{s}$ asymmetry for the strange quark sea.

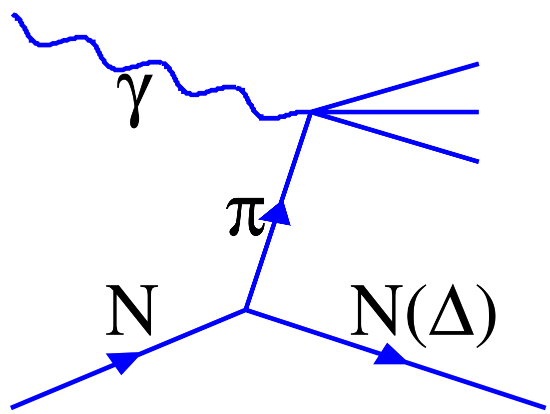


Figure 1: The Sullivan process.

The earliest parton models assumed that the proton sea was flavor symmetric, even though the valence quark distributions are clearly flavor asymmetric. The assumption of flavor symmetry was not based on any known physics, and it remained to be tested by experiments. A direct method to check this assumption is to compare the sea in the neutron to that in the proton by measuring the Gottfried integral in DIS. The Gottfried Sum Rule (GSR) gives the following relation for the proton and neutron structure functions $F_2^p$ and $F_2^n$:

$$I_{GSR} = \int_0^1 [F_2^p(x) - F_2^n(x)]/x \; dx = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)]dx = \frac{1}{3}. \quad (1)$$

In the early 1990s, the NMC collaboration reported [3] an observation of the violation of the GSR [4], $I_{GSR} = 0.235 \pm 0.026$. Since the GSR is derived under the assumption of $\bar{d}(x) = \bar{u}(x)$, the NMC result strongly suggests that this assumption is invalid.

Indeed, Eq. 1 and the NMC result imply that

$$\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = 0.148 \pm 0.039. \tag{2}$$

Independent confirmation of the $\bar{d}/\bar{u}$ flavor asymmetry were later provided by Drell-Yan experiments [5,6,7,8] and the semi-inclusive DIS experiment [9]. Figure 2 shows the E866 result on $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 54$ GeV$^2$/c$^2$. The surprisingly large asymmetry between $\bar{d}$ and $\bar{u}$ is observed over a broad range of $x$. The E866 data provide a direct evaluation of the $\bar{d} - \bar{u}$ integral, namely, $\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = 0.118 \pm 0.012$, which is in good agreement with the NMC result shown in Eq. 2.

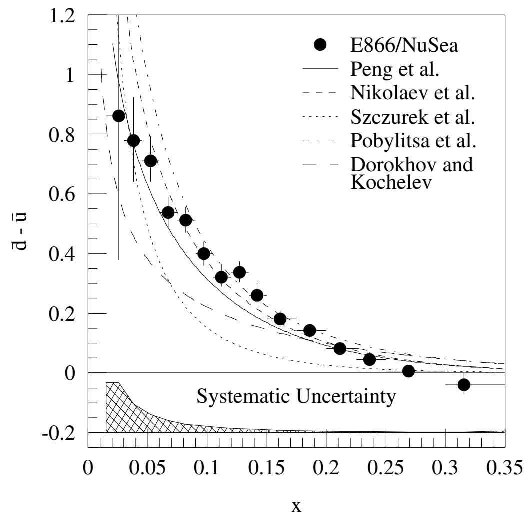


Figure 2: Comparison of the E866 $\bar{d} - \bar{u}$ data with various model calculations [8].

The observation of $\bar{u}, \bar{d}$ flavor asymmetry has inspired many theoretical work regarding the origin of this asymmetry. Perturbative QCD, in which $q\bar{q}$ sea is generated from the $g \to q\bar{q}$ splitting, has difficulties explaining such an asymmetry. The small $d, u$ mass difference (actually, $m_d > m_u$) of 2 to 4 MeV compared to the nucleon confinement scale of 200 MeV does not permit any appreciable difference in their relative production by gluons. At any rate, one observes a surplus of $\bar{d}$ which is the heavier of the two species. Field and Feynman long time ago speculated that the $g \to u\bar{u}$ process would be suppressed relative to $g \to d\bar{d}$ due to Pauli-blocking effect and the presence of two $u$-quarks as compared to a single $d$-quark in proton. Steffen and Thomas have examined the consequences of Pauli-blocking, concluding that the effect of blocking is small. Thus, another, presumably non-perturbative, mechanism must account for the large measured $\bar{d}, \bar{u}$ asymmetry.

Many of the non-perturbative approaches to explain the $\bar{d}, \bar{u}$ asymmetry involve the use of isovector meson (particularly pion). Recent reviews [10,11,12] have extensive discussions on various theoretical models. In the meson-cloud model, the virtual pion is emitted by the proton and the intermediate state is pion + baryon. More specifically, the proton is taken to a linear combination of a "bare" proton plus pion-nucleon and pion-delta states, as below,

$$|p\rangle \to \sqrt{1-a-b}|p_0\rangle + \sqrt{a}(-\sqrt{\frac{1}{3}}|p_0\pi^0\rangle + \sqrt{\frac{2}{3}}|n_0\pi^+\rangle) \tag{3}$$
$$+\sqrt{b}(\sqrt{\frac{1}{2}}|\Delta_0^{++}\pi^-\rangle - \sqrt{\frac{1}{3}}|\Delta_0^{+}\pi^0\rangle + \sqrt{\frac{1}{6}}|\Delta_0^{0}\pi^+\rangle)$$

The subscript zeros on the virtual baryon states indicate that they are assumed to have symmetric seas, so the asymmetry in the antiquarks must be generated from the pion valence distribution. The coefficients $a$ and $b$ are the fractions of the $\pi N$ and $\pi\Delta$ configurations, respectively, in the proton. These fractions can be calculated using the $\pi NN$ and $\pi N\Delta$ couplings, and form factors as taken from experiment. The asymmetry in the proton sea arises because of the dominance of $\pi^+$ among the virtual configurations. Figure 2 shows that the pion-cloud model can reproduce the $x$-dependence of the $\bar{d}-\bar{u}$ distribution very well.

The success of the meson-cloud model in explaining the $\bar{d}, \bar{u}$ asymmetry suggests that a direct measurement of the meson cloud in DIS should be feasible. The idea is that the meson cloud in the nucleon could be considered as a virtual target to be probed by various hard processes including DIS and Drell-Yan. Recently at the HERA e-p collider, meson structure functions were measured in a hard diffractive process, where forward-going neutrons or protons were tagged in coincidence with the DIS events [13]. Figure 3 shows the pion structure function at very low $x$ deduced from such measurement.

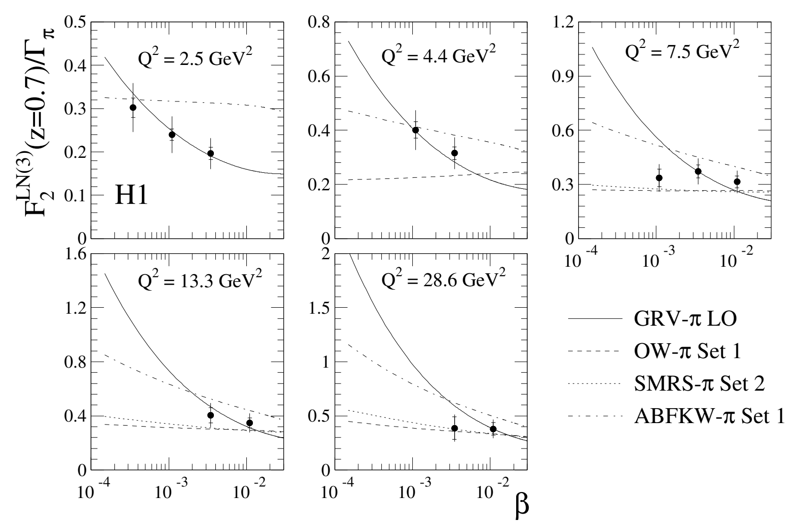


Figure 3: Pion structure functions measured by H1 [13] in comparison with parameterizations of various pion parton distribution functions. The Bjorken-$x$ of the pion is denoted as $\beta$.

While the HERA experiments have provided very interesting first data on the extraction of pion structure functions using the Sullivan process, there are many reasons for extending such measurements to JLab energies. First, the HERA kinematics is limited to very low $x$ region, where no independent measurement of pion structure functions exists. This makes it difficult to check the validity of the interpretation of the HERA data in terms of the meson-cloud model. At the JLab energies, the high $x$ region of the pion would be probed, where some data on the structure functions already exist from the pion-induced Drell-Yan experiments. A comparison of the $x$-dependence of the pion structure function deduced from the Sullivan process and the Drell-Yan process would provide a very stringent test of the pion-cloud model. Second, the large angular and kinematic coverage for the recoiling proton (or proton pair) using the CLAS and BONUS detectors would allow a detailed study of the Sullivan process as a function of variables including the recoiling proton momentum and angles. Third, the CLAS and BONUS detectors would allow a detection of the $\Lambda \to p\pi^-$ decay, making a measurement of the $p \to K^+\Lambda$ kaon cloud in the nucleon potentially feasible. This could lead to a measurement of kaon structure functions. Finally, the Sullivan process could contribute to the proposed $d(e,e'p)X$ measurement of the neutron structure function (E03-012). It is important to determine experimentally the magnitude of the Sullivan process by detecting the $p(e,e'p)X$ and $d(e,e'pp)X$ reactions. Such measurements would provide crucial inputs needed for an accurate extraction of the neutron structure functions.

## 2 The Proposed Measurement

### *2.1 Overview*

We propose to measure the semi-inclusive reaction p(e,e'p)X and D(e,e'pp)X for $Q^2 > 1$ $(\mathrm{GeV/c})^2$ at very low proton momentum (50 - 200 MeV/c). The kinematics for the measurement are chosen so that the deep inelastic scattering occurs from the pion cloud surrounding the proton. The low momentum protons ensure that the virtual pions have a small three momentum and consequently, the pion cloud is spatially large. Thus the key to this experimental technique is to measure the low-energy outgoing proton in coincidence with the scattered electron, which can be achieved by employing the CLAS to detect the scattered electrons and a radial time projection chamber (the BONUS detector) to detect the scattered protons.

In this experiment we will measure the semi-inclusive structure function of the leading proton, $F_2^{LP(4)}$, which is related to the measured cross-section as;

$$\frac{d^4\sigma(ep \to e^{'}Xp^{'})}{dxdQ^2dzdt} = \frac{4\pi\alpha^2}{xQ^4}(1 - y + \frac{y^2K}{2[1+R]})F_2^{LP(4)}(x, Q^2, z, t), \tag{4}$$

where $y = P.q/P.l$, $Q^2 = -(l-l')^2$, $x = Q^2/(2P.q)$, $K = 1 + \frac{M^2X^2}{Q^2}$, and $t = (P - P')$ where $P(P')$ are the initial(scattered) proton 4 vector, $q = l - l'$ and $l(l')$ are the initial (scattered) lepton and $R$ is the ratio of the cross-section for longitudinally and transversely polarized virtual photons. The measured cross-section can be integrated over the proton momentum (which is effectively an integration over $t$ [13]) to obtain the leading proton structure function $F_2^{LP(3)}$. The pion structure function $F_2^{\pi}$ can then be extracted from $F_2^{LP(3)}$ using models, such as the Regge model of baryon production. In the Regge model the contribution of a specific exchange $i$ is defined by the product of its flux $f_i(z,t)$ and its structure function $F_2^i$ evaluated at $(x_i, Q^2)$. Thus,

$$F_2^{LP(3)} = \sum_i \left[ \int_{t_0}^{t_{min}} f_i(z,t) \right] F_2^i(x_i, Q^2), \tag{5}$$

where $i$ is pion, $\rho$-meson, etc, and the $t$ corresponds to the range of $p_T$ analyzed.

The extraction of the pion structure function will have to be corrected for a number of complications to this simple picture, such as the absorptive effect of other mesons. However, these corrections are minimized by measuring at the lowest proton momentum possible from the reaction. This minimizes the absorptive correction since at lower momenta the pion cloud is further from the bare nucleon. In addition, the low proton momentum ensures that the higher meson mass exchanges are suppressed by the energy denominator. These and other corrections will be discussed in the full proposal.

### *2.2 Pion Flux*

The largest uncertainty in extracting the pion structure function arises from the knowledge of the pion flux in the framework of the pion cloud model. One of the main issues is whether to use the $\pi NN$ form factor or the Reggeized form factor. The difference between these two methods can be as much as 20% [17]. From the N-N data the $\pi NN$ coupling constant is known to 5% [18]. If we assume that all corrections can be performed with a 50% uncertainty and we assume a 20% uncertainty in the pion fluxfactor, the overall systematic uncertainty will be 24%. However, by comparing to pionic Drell-Yan data at moderate $x$ (where it is most reliable), we can have a measurement of the pion flux factor. For example the pion structure function at x=0.5 has been measured from the pionic Drell-Yan data to an accuracy of 5% [19].

### *2.3 Kinematics & Modeling*

The cross section depends on the splitting fraction and the electron pion cross section[11]

$$\frac{d\sigma(ep \to e'NX)}{dx_{Bj}\, dQ^2\, dz\, dp_T^2} = f_{N\pi/N}(z, p_T^2)\, \sigma_\pi(x_{Bj}/(1-z), Q^2) \tag{6}$$

with 2/3 of the cross section due to $ep \to e'nX$ and 1/3 due to $ep \to e'pX$. The total cross section also would include contributions from other meson-nucleon Fock states ($\rho N$, etc.), which contributions can be suppressed by restricting the region of $z$ and $p_T$ probed.

The cross sections of $\Delta$ production processes, $ep \to e'\Delta X$, would similarly have contributions from Fock states containing $\pi$ mesons, and could also be used to

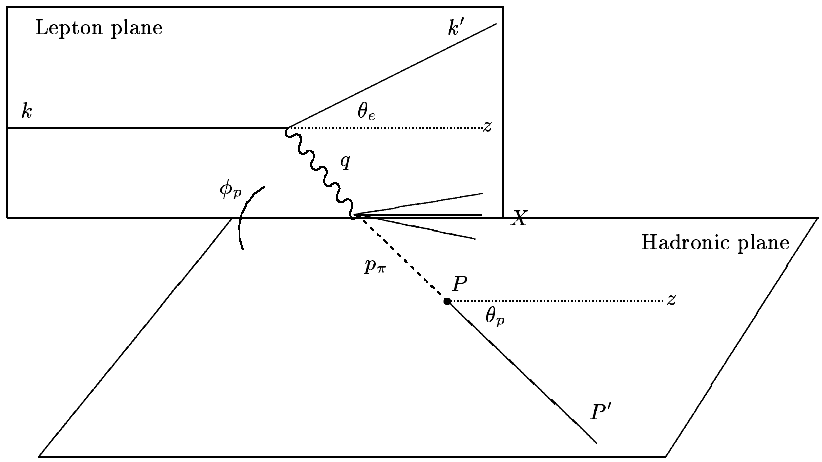


Figure 4: Kinematics diagram for electron scattering from pion cloud of the proton. The initial proton is at rest.

probe the pion structure functions. The splitting functions for the $\Delta$ contributions[20] are about half of those for the proton final state, but extend closer to $z = 1$. These contributions have not been calculated in this study.

The pion nucleon splitting function is given by[20]

$$f_{N\pi/N}(z, p_T^2) = \frac{3g^2_{p\pi^0 p}}{16\pi^2 Z^2(1-Z)} \left[\frac{\Lambda_\pi^2 + M_p^2}{\Lambda_\pi^2 + M_{\rm inv}^2}\right]^2 \left[\frac{M_p^2(1-Z)^2 + p_T^2}{(M_p^2 - M_{\rm inv}^2)^2}\right] \tag{7}$$

with the invariant mass of the Fock state

$$M_{\rm inv}^2 = \frac{M_p^2 + p_T^2}{Z} + \frac{M_\pi^2 + p_T^2}{1-Z} \tag{8}$$

and taking the $\pi NN$ vertex form factor to be the dipole form with a cutoff parameter taken as $\Lambda_\pi = 0.7$ GeV/c$^2$.

Table 1: Kinematic terms for electron scattering from pion cloud of the proton as diagrammed in Figure 4.

$$\begin{aligned}
q &= k - k' \\
\nu &= E - E' \\
Q^2 &= -q^2 \;=\; 4\,E\,E'\,\sin^2\frac{\theta_e}{2} \\
x_{Bj} &= \frac{-q^2}{2\,p\cdot q} \;=\; \frac{Q^2}{2\,M_N\,\nu} \\
y &= \frac{p\cdot q}{p\cdot k}
\end{aligned}$$

$$\begin{aligned}
z &= \frac{p'\cdot q}{p\cdot q} \\
p_\pi &= p - p' \\
t &= p_\pi^2 \;=\; 2\,M_N^2 - 2\,p\cdot p' \\
x_\pi &= x_{Bj}/(1-z) \\
y_\pi &= \frac{p\cdot q\,(1-z)}{p\cdot k - p'\cdot k} \\
p'\cdot k &= E\,E'_p - E\,|\vec{p'}|\cos\theta_p
\end{aligned}$$

The electron-pion cross section has been calculated from the GRV pion parton distribution functions[21], as included in the PDFLIB package[22], using the same functional form as the proton

$$d\sigma_\pi(x_{Bj}/(1-z), Q^2) = \frac{2\,\pi\,\alpha_e^2}{x_\pi\,Q^4}\left[\,\left(2-2Y_\pi+(2-K)Y_\pi^2\right)\,F_2^\pi(x_\pi,Q^2) - KY_\pi^2\,F_L^\pi(x_\pi,Q^2)\right] \tag{9}$$

where $K = 1+\frac{m_\pi^2 X^2}{Q^2}$, and the pion form factors are defined in the same way as for the nucleon[23]:

$$F_2^\pi(x_\pi,Q^2) = x_\pi \sum_{q=u,d,s} e_q^2\left[q(x_\pi,Q^2)+\bar{q}(x_\pi,Q^2) + \frac{\alpha_s(Q^2)}{2\pi}\left(C_{q,2}\otimes(q+\bar{q})+2C_{g,2}\otimes g\right)\right] \tag{10}$$

$$F_L^\pi(x_\pi,Q^2) = x_\pi\frac{\alpha_s(Q^2)}{2\pi}\sum_{q=u,d,s} e_q^2\left[C_{q,L}\otimes(q+\bar{q})+2C_{g,L}\otimes g\right] \tag{11}$$

with the convolution defined

$$C\otimes q = \int_{x_\pi}^1 \frac{dy}{y}C(x/y)q(y,Q^2) \tag{12}$$

and the Wilson coefficients:

$$C_{q,2}(z) = \left[\frac{1+z^2}{1-z}\left(\ln\frac{1-z}{z}-\frac{3}{4}\right)+\frac{1}{4}(9+5z)\right] \tag{13}$$

$$C_{g,2}(z) = \frac{1}{2}\left[(z^2+(1-z)^2)\ln\frac{1-z}{z} - 1 + 8z(1-z)\right] \tag{14}$$

$$C_{q,L}(z) = \frac{8}{3}z \tag{15}$$

$$C_{g,L}(z) = 2z(1-z) \tag{16}$$

The integrand of the convolution $C_{q,2}\otimes(q+\bar{q})$ diverges at the lower limit of integration; the convolution is calculated as[24]

$$\int_x^1 \frac{dy}{y}f(x/y)g(y) = \int_x^1 \frac{dy}{y}f(x/y)\left[g(y)-x/yg(x)\right] - g(x)\int_0^x dyf(y) \tag{17}$$

### *2.4 Simulation & kinematic coverage*

The pion cloud contributions to the proton cross section were calculated as described in Section 2.3, with an incident electron beam energy of 6 $GeV$, over the range: $1.0 < Q^2 < 2.5$ in $(GeV/c)^2$, $0.055 < x_{Bj} < 0.455$, $0.6 < z < 1.0$, and $0.0 < p_T < 0.5$ in $GeV/c$. The accepted events required: $E_{out} > 0.25$ GeV, $z < 1 - x_{Bj}$, $t > -0.1$,

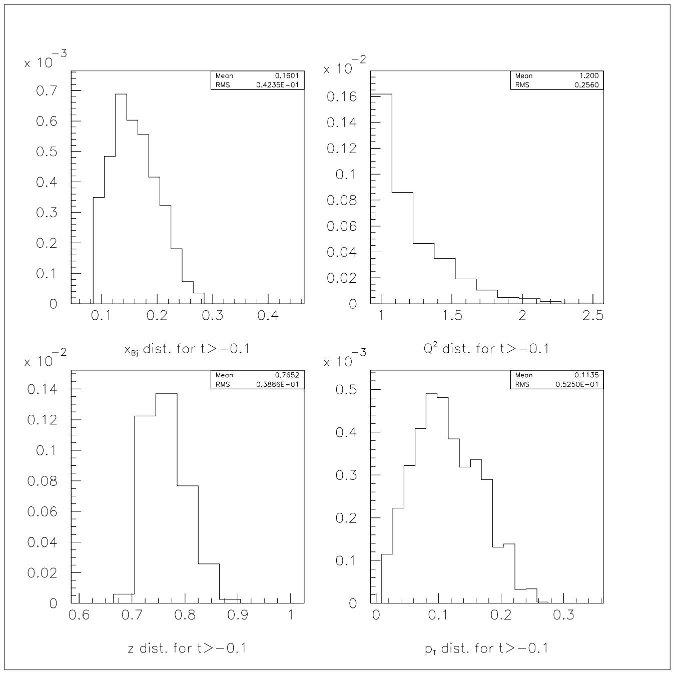


Figure 5: The rate in arbitrary units plotted versus $Q^2$ in (GeV/c)$^2$, $x_{Bj}$, $z$, and $p_T$ in (GeV/c).

$W_X^2 \geq m_\pi^2$. The estimated rates in arbitrary units are shown as functions of $Q^2$, $x_{Bj}$, $z$, and $p_T$ in Figure 5. The expected rates can be estimated by considering the total number of virtual pions in the nucleon[20,11]: the $N\pi$ and $\Delta\pi$ Fock states contribute 18% and 6% to the nucleon, so the deep inelastic scattering on a pion which has been fragmented from the nucleon should be only an order of magnitude lower than for the inclusive *ep* scattering.

The recoil protons associated with this process are dominantly at low scattering angles with respect to the beam line, and at relatively high momentum compared to the sensitivity of the BONUS detector. The measurements on the proton may be more suitable to detection of both the electron and proton in CLAS, instead of using BONUS and CLAS.

The simulation for scattering from a deuterium target has not yet been done. With a deuterium target, the initial nucleon will have Fermi energy, and so the available kinematics of the virtual meson and the recoil baryon should include rate at higher nucleon scattering angles.

## 3 The Experiment

The proposed experiment will use the JLab 6 GeV unpolarized electron beam with the maximum current available to Hall B; a beam current of 200 nA was used in the BONUS proposal, and that beam current has been used for the rate estimates in this paper. The target will be the hydrogen/deuterium gas cell being designed for the BONUS experiment. We will detect the scattered electrons in CLAS and low momentum protons will be detected in the RTPC.

The BONUS experiment is developing a novel, GEM-based, radial time projection chamber (RTPC) with a low momentum threshold for protons, and a high rate capability. This detector will allow tagging of slow, backward-moving spectator protons with momenta as low as 70 MeV/c and up to at least 200 MeV/c, in coincidence with a scattered electron or other particle in the Hall B CLAS spectrometer. The RTPC is a small barrel, 20 cm long and about 13 cm in diameter, surrounding a thin gas target. In the BONUS configuration, protons may be detected for lab scattering angles between 12 and 150 degrees. However, moving the target back (a simple change to implement) would allow for extension to smaller angles. For the experiment being suggested in this letter, both hydrogen and deuterium gases would be used. Electrons will be detected in CLAS in coincidence with protons in the RTPC, with a common vertex, resolvable to better than 0.5 cm. Pions can be distinguished from protons in the RTPC by comparing track curvature in the solenoid in which the target and RTPC reside, and by energy loss in the active RTPC detector volume. For a more detailed discussion of this target and detector system, please see the BONUS proposal, available on the web at `www.jlab.org/exp_prog/generated/apphallb.html`.

We note that higher momentum protons can be detected using CLAS alone, as was done in the E6 experiment. Here, a minimum angle of about 10 degrees should be possible (running the CLAS toroid in positive mode), with a minimum momentum of about 300 MeV/c. This last number depends on the target configuration, and one could consider lowering this number via the use of a very small diameter liquid cell. As the proposed experiment is optimized, a best choice of the possible options for target and detector configuration can be made.

## 4 Relation with other experiments

### *4.1 Relation to E03-012, "The Structure of the Free Neutron Via Spectator Tagging"*

Hard scattering of the electron from the pion cloud of either the proton or the neutron is a potential background process of some concern to the approved BONUS inclusive neutron structure function measurement[?], as it would be indistinguishable from the coincident scattered electron plus spectator proton measurement of interest. The BONUS measurement is proposed for a different kinematic regime (backward angle, low momentum protons) than that here discussed, and it appears preliminarily that the background rates due to hard scattering from the pion cloud should be quite small for BONUS kinematics. However, we note that the experiment here proposed can verify this, and remove this uncertainty entirely from the BONUS measurement.

### *4.2 Relation to PR01-110, "The H(e,e'n)X Reaction and the Pion Structure Function"*

The physics goals and kinematic coverage of this experiment are very close to those of proposal[?] PR01-110. The difference is that the recoil protons produced in the $p(e,e'p)X$ and $d(e,e'pp)X$ processes described in this paper are technically easier to measure than the final state containing the neutron discussed in PR01-110.

## 5 Summary

The described calculations for Deep Inelastic electron Scattering on the meson cloud of the proton indicate that the recoil protons associated with this process are dominantly at low scattering angles with respect to the beam line, and at relatively high momentum compared to the sensitivity of the BONUS detector. The measurements on the proton's meson cloud may be more suitable for a measurement using only the CLAS detector, instead of both CLAS and BONUS.

One additional concern for these measurements on a proton target is that at the upper $z$ range contributions from pomeron exchange become significant[20].

The process $D(e,e'pp)X$, where the electron scatters from a $\pi^-$ split from the neutron may be more suitable for measurements using the BONUS detector.

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